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High spectral resolution spectroscopy of sprites: A natural probe of the mesosphere

F. J. Gordillo-Vaázquez, M. Passas, A. Luque, J. Saánchez, O. A. van der Velde, J. Montanya

We present the first high spectral resolution (0.24 nm) spectra of sprites. These spectra were recorded in Europe in the summers and falls of 2015 and 2016 and during January 2017. The use of high-spectral resolution has allowed us to resolve for the first time the internal (vibro-rotational) structure of the sprite molecular N₂ first positive system and to quantify the local gas (rotational) temperature of the mesosphere under the influence of sprites revealing that there is no measurable heating of the atmosphere associated to sprites at the altitudes explored. The temperatures of the explored region of the mesosphere range between $149\text{ K} \pm 10\text{ K}$ and $226\text{ K} \pm 20\text{ K}$.

The recorded spectroscopic data also provide valuable quantitative information on the concentrations of some of the vibrational levels of molecular nitrogen involved in transient red-near infrared optical emissions from sprites. The regions of the TLEs recorded with our spectrograph (equipped with a horizontally oriented slit) correspond to altitudes in the 66 km - 74 km ± 5 km range.

1. Introduction

Soon after the publication of the first Transient Luminous Event (TLE) images (of a sprite) recorded during the night of 22 to 23 September 1989 [Franz et al., 1990], the interest of the international community in TLE spectroscopic features started since spectra of TLE can inform about the type of molecules that produce optical emission, their degree of vibrational and electronic excitation and if TLEs are able (or not) to produce a possible and measurable heating of the surrounding atmosphere. Previous works [Mende et al., 1995; Hampton et al., 1996] reported the first spectroscopic studies of the N₂ first positive band system ($\text{FPS, B}^3\Pi_g \rightarrow \text{A}^3\Sigma^+u$) from the "body" of sprites occurring between 70 km and 90 km of altitude. These early spectral investigations of TLEs used regular (30 fps) video recording in the visible and near infrared (NIR) spectral range (550 nm - 840 nm) and low (above 6 nm) spectral resolutions. Unfortunately, the number of spectroscopic campaigns of TLEs since the mid 1990s has been scarce. Later results [Morrill et al., 1998; Bucsela et al., 2003] reported spectroscopic investigations of the low altitude "tendrils" (blurred motion of rapidly moving point-like structures [Liu and Pasko, 2005; Stenbaek-Nielsen et al., 2007]) of sprites at 53 km and 57 km covering from 600 nm up to 900 nm with low

spectral resolutions of 7 nm and 11 nm, respectively. More recently it has been reported altitude resolved sprite spectra of the N2 FPS with an imaging (vertical) slit spectrograph within 640 nm - 820 nm with 3 ms (300 fps) temporal and ~3 nm spectral resolutions [Kanmae et al., 2007].

Regarding near ultraviolet (NUV) (below 400 nm) spectra of sprites, the only measurements available to date (without correction for instrument response function) are those

focusing on optical emissions of the N2 second positive band system ($\text{SPS}, \text{C}^3\text{Pu} \rightarrow \text{B}^3\Pi\text{g}$) from the "body" of sprites at 65 km altitude [Heavner et al., 2010]. This NUV sprite spectrum was recorded during the EXL98 observation campaign from an aircraft at 14 km altitude and using ~4 nm spectral resolution and 60 fps recording rate.

High-speed (10,000 fps) slitless spectroscopy of sprite streamer heads and column-shaped glows were reported for the first time in 2010 from aircraft observations including blue spectral features [Kanmae et al., 2010a] and from ground-based facilities [Kanmae et al., 2010b] with the spectra consisting only of the N2 FPS due to the atmospheric absorption of the blue component through the long line of sight. The different types of TLEs occurring in the Earth's atmosphere from the lower stratosphere to the upper mesosphere can be considered as natural probes to learn about the properties of the middle and upper atmosphere of our planet through remote determination of key properties such as the gas temperature or the degree of excitation and ionization of atoms and molecules caused by TLEs in the atmosphere. In this regard, systematic spectroscopic campaigns of optical emissions from all sort of TLEs can allow us to remotely determine important atmospheric properties that would be difficult to obtain in other ways. Unfortunately the spectrographs used in the dispersed TLE spectroscopic campaigns carried out so far were originally designed for aurora spectroscopy [Hallinan et al., 1985] and the best spectral resolution achieved to date is ~3 nm which it is not enough to spectrally resolve the different low-lying vibrational transitions of the N2 FPS.

The lack of TLE spectroscopic observations with high-spectral resolution motivated us to build a TLE-dedicated instrument called GRAnada Sprite Spectrograph and Polarimeter (GRASSP). This spectrograph has a mean spectral resolution of 0.24 nm (with a linear dispersion of 0.07 nm/pixel) and covers the wavelength range between 700 nm and 800 nm with 40 ms (25 fps) temporal resolution [Passas et al., 2016b] (see supplementary information for details). GRASSP is in operation for ground-based systematic imaging and spectroscopic surveys of all sort of TLEs in Europe since October 2012 when the first GRASSP version [Parra-Rojas et al., 2013b] was deployed in the Calar Alto Astronomical Observatory (CAHA) (37°13' 23" N 23°45' W) placed 2168 m above sea level in South-east Spain. GRASSP recorded from CAHA many images of distant TLEs [Passas et al., 2014] and carried out meteor spectroscopy [Passas et al., 2016a]. An upgraded version of GRASSP is now available and relocated (since May 2015) in Castellgali (Barcelona, 41°40' 36" N 150°24' E) placed 266 m above sea level and close to the Ebro valley.

As we describe below, GRASSP has allowed to resolve for the first time the vibrational bands of N₂ FPS in transient air plasma spectra generated by TLEs and to remotely determine the gas temperature in the mesosphere and if there is any measurable heating due to sprites at the altitudes explored. We have calculated the approximate altitudes of the TLEs regions whose spectra are recorded and we have correlated them with the derived gas temperatures. A more detailed discussion on the methodology followed for sprite altitude determination can be found in the supplementary information [van der Velde and Montanyà, 2016; S'ao Sabbas et al., 2003]. Furthermore, we present quantitative measurements of the relative vibrational concentrations of the emitting electronic state N₂(B₃Πg, v) from carrot, single-column and multi-column-like sprites and compare with previous measurements and theoretical calculations.

2. Observations and Results

TLE activity during the 2015 campaign was relatively high in south-western Europe. However, the number of sprites recorded with GRASSP was low. A total of 3 events were recorded with the spectrograph with good quality data obtained from carrot and column-like sprites occurring in a range between 350 km and about 800 km. In general, spectra are only present in one frame due to the low available temporal resolution and the peaked brightness profile of sprites.

Sprite spectra (see Table 1) were recorded from Castellgali, Spain, 266 m above sea level at 01:15:26 UTC (event 1) and 01:20:55 UTC (event 2) on 24 August 2015 and 04:07:44 UTC on 28 September 2015 (events 3a and 3b). Two distant clusters of carrot-like sprites were recorded on 24 August 2015 over a thunderstorm in northern Italy (see top panel of Fig. 1). On 28 September 2015 a close column-like sprite was recorded over a thunderstorm in the south of the Balearic islands (see bottom panel of Fig. 1). The maps in Fig. 1 show the location of the parent lightning producing sprites detected at 01:15:26 UTC and 01:20:55 UTC on 24 August 2015 (top panel) and at 04:07:44 UTC on 28 September 2015 (bottom panel). The lightning detection network used was LINET [Betz et al., 2008]. The images shown in Fig. 1 were recorded by Meteosat Second Generation (MSG) and the color bar in the lower right corner of the top image refers to cloud-top temperatures. Regarding the size and color of the circles in Fig. 1, the size scales with peak current (which is labeled). The different colors of the circles refer to the number of sprite events produced by those lightning and that we got spectra.

Fig. 2 shows scene camera images of two carrot sprites (events 1 and 2) and one multi-column sprite (events 3).

The TLE spectroscopic campaigns during 2016 and January 2017 were more fruitful than the one of 2015. Up to the end of January 2017 a total of 32 events were recorded with GRASSP. The events included carrot and column-like sprites as well as precursory halos to some of the detected sprites. The four bottom images shown in Fig. 2 correspond to the 2016 and 2017 sprites analysed in this work.

The 2016 and January 2017 TLE spectra were also recorded from Castellgali, Spain (see scene camera images in the third and fourth rows of Fig. 2). The TLE spectra on 14-15 September, 2016 were recorded over southeastern France (area around 4-8E and 43-46N) at 23:47:20 UTC, 23:55:35 UTC, 01:12:59 UTC (event 4) and 01:16:38 UTC. Two additional carrot sprite spectra were recorded on October 21, 2016 over east of Menorca island (Spain) at 01:24:19 UTC and 01:37:01 UTC. A total of 24 sprite spectra were recorded between November 2016 and January 2017. However, only some of them presented good signal to noise ratio (SNR). In particular, we have chosen the ones that occurred at 02:23:07 UTC (event 5) on 16 November 2016, 23:37:32 (UTC) (event 6) and 23:40:35 UTC (event 7) on 17 January 2017.

The N₂ FPS (2, 0) rovibronic band spectra of the two recorded carrot-like sprites (event 1 and event 2) were fitted with synthetic spectra following previously described procedures [Parra-Rojas et al., 2013b]. A more detailed discussion on the fitting procedure can be found in the supplementary information [Simek, 1994; Simek and De Benedictis, 1995; Biloiu et al., 2007; Herzberg, 1950]. Fig. 3 shows good agreement between the recorded (green line) and fitted synthetic (blue line) spectra of two carrot sprite spectra corresponding to event 1 and event 2. Due to the long slant path (between 300 and around 800 km) the spectroscopic signal from TLEs can be strongly affected by absorption from various atmospheric constituents (O₂, H₂O, CO₂). To quantify this effect, we have estimated atmospheric transmittance using MODTRAN 5 [Berk et al., 2005] in the 700 - 800 nm spectral range with the observing site (Castellgali, Spain) at only 266 m above sea level (see transmittance curves in supplementary information). All spectra shown in Fig. 3 clearly exhibit the expected three main peaks of the (2, 0) band of the N₂ FPS located, respectively, in the spectral positions 774.8 - 775.4 nm (band head peak), 773.5 - 774.1 and 771.0 - 771.6 nm (see supplementary information), [Simek, 1994].

The rotational gas temperatures (T_{rot}) from the fitted spectra in Fig. 3 corresponding to two different carrot sprite events (event 1 and event 2) captured during the 2015 campaign, are 185 K ± 10 K (event 1) and 190 K ± 11 K (event 2). The calculated uncertainties of the derived gas temperatures correspond to the standard deviation σ (square root of the variance) obtained from the numerical least-square fitting of synthetic spectra to the recorded spectra. These estimated uncertainties are probably underestimating the real error.

Also shown in Fig. 3 are the spectra of different regions of a multi-column sprite recorded at 04:07:44 UTC on 28 September 2015. In particular, the recorded (green line) and fitted spectra (blue line) are those corresponding to event 3a and event 3b which are marked with red circles in Fig. 2. The recorded column sprite spectra (second row of Fig. 3) are a bit noisier than the ones of the carrot sprites (first row of Fig. 3) because the available optical signal is weaker. According to parent lightning location, the analysed column like sprites occurred closer (\approx 350 km) to the observing site (see bottom panel of Fig 1) than the detected carrot sprites (\approx 800 km). Even though, the spectral fit of the (2, 0) rovibronic transition in the recorded multi-column spectra remains quite reasonable with clear visibility of the three main peaks of the (2, 0) band of the N₂ FPS. The rotational gas temperatures (T_{rot}) derived from the synthetic spectra fitting to single-column spectra shown in Fig. 3 are 149 K ± 10 K (event 3a) and 210 K ± 24 K (event 3b).

The spectrum of the event 4 corresponds to the leftside columnar structure of the carrot sprite partially hidden by trees as seen in Fig. 2. In all these spectra the three main peaks of the (2, 0) band of the N₂ FPS are distinctly visible.

The rotational gas temperatures (T_{rot}) derived from the 2016 and 2017 fitted spectra in Fig. 3 are $178\text{K} \pm 10\text{K}$ (event 4), $164\text{K} \pm 18\text{K}$ (event 5), $226\text{K} \pm 17\text{K}$ (event 6) and $201\text{K} \pm 20\text{K}$ (event 7). Table 1 shows that the derived gas temperature fluctuates depending on the type of sprite probing different altitudes of the mesosphere.

Fig. 4 shows the full (green line) spectra recorded by GRASSP and the corresponding fitted spectra (blue line) using the same 0.24 nm spectral resolution. The gas temperatures used to generate the fitted synthetic spectra in Fig. 4 are shown in Table 1 and they are derived from the rotational fits of the (2, 0) band in the spectra of events 1, 3a, 4, 5 and 7 (see Fig. 3). The synthetic spectra are for neutral N₂ only and it includes six $\Delta v = 2$ rovibronic band transitions marked in the plots of the N₂ (B³ $\Pi_g \rightarrow$ A³ Σ^+u) electronic transition.

3. Discussion

Sprite spectra recorded with GRASSP during the spectroscopic campaigns of 2015, 2016 and January 2017 from Spain are the first high resolution spectra of TLEs to date. The spectral resolution used (0.24 nm) has allowed us to resolve the rovibrational structure of $\Delta v = 2$ bands of the N₂ FPS within the explored spectral range (700 - 800 nm) from an almost sea level (266 m) observation site. We captured high resolution spectra of full carrot sprites, single-column sprites (see red circles in the second row of Figure 2) as well as multi-column sprites. Figure 2 shows the different morphologies of recorded sprites covering a range of altitudes between $66 - 67\text{ km} \pm 5\text{ km}$ (lower region of a multi-column sprite - event 3) and $71 - 72\text{ km} \pm 5\text{ km}$ (column sprite - event 6). Note that we give the altitudes (and corresponding error) associated to the lower and upper limit of the spectrograph slit.

Figure 3 shows high resolution spectra of the (2, 0) band of the N₂ FPS associated to each of the sprites in Figure 2. We can see that the (2, 0) band is well resolved and that the spectra with the best signal to noise ratio (SNR) correspond to carrot sprites since they produce higher and more uniform optical signal in the spectrograph slit than the narrow regions of the recorded single and multi-column sprites.

Contrary to the assumed rotational (gas) temperatures reported in previous low resolution sprite spectra [Mende et al., 1995; Hampton et al., 1996; Kanmae et al., 2007], our high-resolution TLE spectroscopic campaigns have allowed us to extract the rotational temperature from the fitting shown in Figure 3 of the recorded and synthetic spectra of the N₂ FPS (2, 0) band.

The analysis of highly resolved spectra associated with the altitude localization of sprites makes them a useful "mesospheric thermometer". Table 1 shows that the derived gas temperature fluctuates depending on the type of sprite probing different altitudes of the mesosphere. The mesospheric temperatures obtained from high-resolution spectra of sprites are in reasonable agreement with previous temperature measurements performed from 1978 to 1989 by two Rayleigh lidars [Hauchecorne et al., 1991] in the south of France (44°N , 6°E and 44°N , 1°W) close to our spectroscopic

recordings. Table 1 also includes meso-spheric temperatures recorded by the instrument SABER on board the satellite TIMED in the region, altitudes and times explored in this work. SABER provides temperature profiles from 20 to 105 km, retrieved from CO₂ 15 μ m emission with 1.5 - 2 K errors in the 60-80 km range [García-Comas et al., 2008]. Most of temperature measurements are 20 K below available LIDAR and SABER measurements except in one case - event 3a - where it is about 70 K below. This is only explained by the uncertainty of the fitting procedure. The quality of the fitting is controlled by the noise in the observed spectra. Our lowest error is $\approx 5\%$ ($185\text{ K} \pm 10\text{ K}$) while the errors of both the LIDARs and SABER are $\approx 1\%$. Sprite spectra are transient by nature and this introduces an additional complication. Spectroscopy of a sprite single-column is specially challenging because much less photons are collected (considered) and the SNR is worst which produce noiser spectra. This is the case of event 3a where the difference with the LIDARs and SABER gas temperatures is almost 70 K. There is also a lack of statistics: to probe the mesosphere temperature by means of fitting TLE spectra with theoretical models we need a larger amount of data that might allow us to measure the mesosphere temperature in a more consistent way.

The temperature values obtained indicate that there is no measurable heating of the mesosphere due to the presence of sprites within the range of altitudes explored in this work. Due to the scarce number of measurements, it is hard to identify a clear trend in the temperatures shown in Table 1. In this regard, one is tempted to see a seasonal behaviour in the measured temperatures of the mesosphere but available data are too little.

It is worth mentioning that the recorded high-resolution spectra only show spectroscopic features of neutral molecular nitrogen. In particular the recorded high-resolution (2, 0) band spectra of the N₂ FPS in carrot, single-column and multi-column sprites did not show any traces of the strong 777.4 nm atomic oxygen (O I) triplet line usually seen in lightning spectra in the troposphere. While the mechanisms of energy dissipation in lightning are controlled by high currents (of typically tens of kA and tens of milisecond duration) and very frequent collisions in a high pressure environment, energy dissipation in sprites and halos is controlled by impulsive high reduced electric fields transferring energy to electrons in a low pressure ambient. Therefore, energetic electrons in sprites and halos can excite molecules but also, depending on how high is the gained energy, electrons can dissociate and ionize N₂ and/or O₂ molecules [Adachi et al., 2008; Luque and Ebert, 2009; Hiraki, 2010; Gordillo-Vázquez et al., 2011; Williams et al., 2012; Parra-Rojas et al., 2013a]. Sprites generally exhibit an upper (85 - 75 km) diffuse structure and a lower (75 - 40 km) filamentary region where thousands of streamers develop and where reduced electric fields can reach values of 400 - 600 Td [Pasko et al., 1998; Luque and Ebert, 2010; Stenbaek-Nielsen et al., 2010] that activate complex nonequilibrium electron-driven kinetics in low pressure air [Gordillo-Vázquez, 2008; Sentman et al., 2008; Parra-Rojas et al., 2015]. In particular, the production of the 5P electronic state of O I, whose radiative decay produces the 777.4 nm line, could be activated by (i) electron impact dissociative excitation of O₂ ($e + O_2 \rightarrow O + O(5P) + e$) generating ground state O I atoms and electronically excited O(5P) atoms and (ii) direct electron impact excitation of ground state free ambient O I atoms producing electronically excited O(5P) atoms

($e + O \rightarrow O(5P) + e$). The rate coefficients of mechanisms (i) and (ii) in low pressure (mesospheric) dry air increase as the reduced electric field grows but the production of $O(5P)$ by dissociative excitation is always significantly higher than the one by direct electron impact excitation from ground state oxygen atoms. Therefore, it could be possible that 777.4 nm optical emissions appear in well-resolved sprite spectra. The possible 777.4 nm emission would not be uniformly produced through the entire body of the sprite but only in regions with high enough reduced electric fields like well developed streamers in sprites and/or in regions of sprites where streamer reconnection occur. However, none of the spectra of our detected sprites in the 66 km - 74 km \pm 5 km region exhibit the characteristic 777.4 nm lightning emission feature that could be more probable in lower altitudes (50 - 55 km) regions of sprites. Figure 4 shows high resolution observed spectra (green line) of carrot sprites (panels 1 and 3), single column sprite (panel 2) and multi-column sprites (panel 4 and 5). None of the spectra shown in Figure 4 indicate the possible presence of optical transitions associated to the (2, 0) band (around 785 nm) of N_2^+ Meinel emissions or to the 777.4 nm emission from the 5P electronic state of O I. The fit of high resolution (0.24 nm) synthetic spectra (blue line) to observed sprite spectra shown in Figure 4 is very good for carrot sprites while it is reasonable for the others. These fits allow us to derive the vibrational distribution function (VDF) or populations of the lower (from $v' = 2$ up to $v' = 7$) vibrational levels of the $B^3\Pi_g$ electronic state of N_2 that are shown in Fig. 5 for carrot (left) and single-column and multi-column (right) sprites, respectively. The uncertainties in the derived relative vibrational populations range between 2 % and 5 %. The VDFs derived from fits are compared to: (1) VDF of the $B^3\Pi_g$ state from previous spectroscopic observations (squares and dashed green lines) [Kanmae et al., 2007] of carrot-like sprites at 71 - 75 km altitude using 3 nm spectral resolution and (2) model calculated sprite VDFs (open circles and dashed blue line) at 74 km altitude [Luque and Gordillo-Vázquez, 2011; Gordillo-Vázquez et al., 2012]. In particular, Fig. 5 (left) includes VDFs of carrot sprites corresponding to events 1 and 4. Our carrot sprite VDFs deviate from previous observations for $v' = 3$ and $v' = 4$ while the agreement with VDF model predictions is reasonable except for $v' = 4$. Note that our two shown VDFs from carrot sprites observed at similar altitudes exhibit close values to [Kanmae et al., 2007]. The right panel of Fig. 5 includes VDFs from event 3a-3b and events 5 and 7. The altitude dependence of event 5 and 7 VDFs follows the trend previously reported within a carrot sprite [Kanmae et al., 2007], that is, higher vibrational population for sprites at higher altitudes. However the VDF of the single-column sprite (event 3a-3b) does not follow the above mentioned altitude-dependent trend for $v' = 3$.

4. Summary

High-resolution systematic spectroscopic campaigns of TLEs have been carried out in Europe during 2015, 2016 and early 2017. It is the first time that the (2, 0), (3, 1), (4, 2) and (5, 3) rovibrational bands of the N_2 FPS are well resolved in sprite spectra. We found that the rotational (gas) temperature derived from sprite spectra changes between 149 K \pm 10 K at 66 - 67 km \pm 5 km in September 2015 and 226 K \pm 17 K at 71

- 72 km \pm 5 km in January 2017. However, no measurable heating was detected. Therefore, the possibility to extract mesospheric local gas temperatures from high resolution sprite spectra makes sprites a natural thermal probe of (generally difficult to access) regions of the mesosphere located at different altitudes. However, there is also a lack of statistics in our gas temperature measurements. To probe the mesosphere temperature with more accuracy by means of fitting TLE spectra we would need a larger amount of data.

It is also found that the altitude dependence of vibrational populations in multi-column sprites is similar to the one previously reported within carrot sprites. However, the carrot sprite altitude dependent VDF trend is not completely fulfilled when comparing the VDFs from single-column and multi-column sprites recorded at various altitudes. No spectroscopic features of Meinel N₂⁺ nor 777.4 nm (O I) optical emissions were found in any of our recorded high resolution spectra of sprites at the altitudes explored.

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